Localization of virtual sound sources in realistic and complex scenes: how much do hearing aids alter localization?

Müller, M F ; Kegel, A ; Schimmel, S M ; Dillier, N

Abstract: The human auditory system relies strongly on differences in time and intensity between the two ears to localize correctly a sound source. Bilateral or independent hearing aids distort this information. Van den Bogaert, et al. (2005) showed that, in an anechoic environment, sound localization is better without hearing aids than with. In this study, we investigated how hearing aids modify our localization ability in realistic conditions. With the idea in mind of extending the test situations to arbitrary acoustical environments, virtual acoustics were used as a tool for reproducing sound. The first experiment presented in this paper evaluates sound localization in noise and compares external playback through loudspeakers with the simulations. In a second experiment, we extended our system for virtual acoustics by simulating actual hearing aid algorithms as well. The algorithms implemented are a static beamformer, a monaural noise canceller and the omnidirectional situation, in which the microphone signal is fed directly to the system. The same test conditions as in experiment 1 were reproduced and hearing aid localization was compared to the unaided condition.

Localization of virtual sound sources in realistic and complex scenes: how much do hearing aids alter localization?

Martin F. Müller, Andrea Kegel, Steven Schimmel and Norbert Dillier

Laboratory for Experimental Audiology, University Hospital Zürich

Introduction

The human auditory system relies strongly on differences in time and intensity between the two ears to localize correctly a sound source. Bilateral or independent hearing aids distort this information. Van den Bogaert, et al. (2005) showed that, in an anechoic environment, sound localization is better without hearing aids than with.

In this study, we investigated how hearing aids modify our localization ability in realistic conditions. With the idea in mind of extending the test situations to arbitrary acoustical environments, virtual acoustics were used as a tool for reproducing sound. The first experiment presented in this paper evaluates sound localization in noise and compares external playback through loudspeakers with the simulations. In a second experiment, we extended our system for virtual acoustics by simulating actual hearing aid algorithms as well. The algorithms implemented are a static beamformer, a monaural noise canceller and the omnidirectional situation, in which the microphone signal is fed directly to the system. The same test conditions as in experiment 1 were reproduced and hearing aid localization was compared to the unaided condition.

Methods

To simulate perceptually convincing virtual environments, we combined individual head-related transfer functions (HRTFs) with room simulations (Schimmel et al., 2009). HRTFs model the acoustic path from the precise position of the source to the left and right ears in an anechoic environment. Reflections on the shoulders, the effects of the pinna, head shadow and travelling delay are all described by the HRTFs.

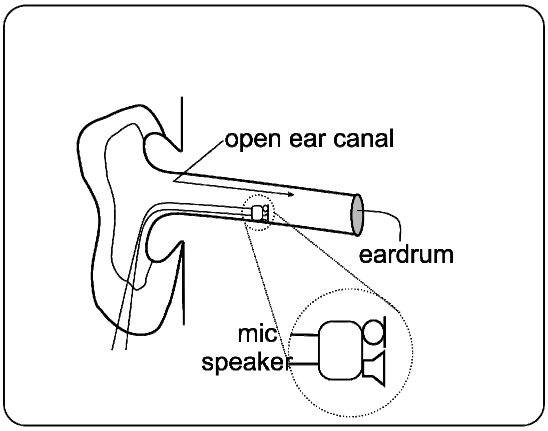

***Figure 1**: Open CIC prototype*

For the measurement of the HRTFs and the reproduction of sound, we developed individual open completely-in-the canal (CIC) shells. We placed a microphone and a speaker in the empty shell, close to the eardrum. The CIC prototypes are shown in Fig. 1.

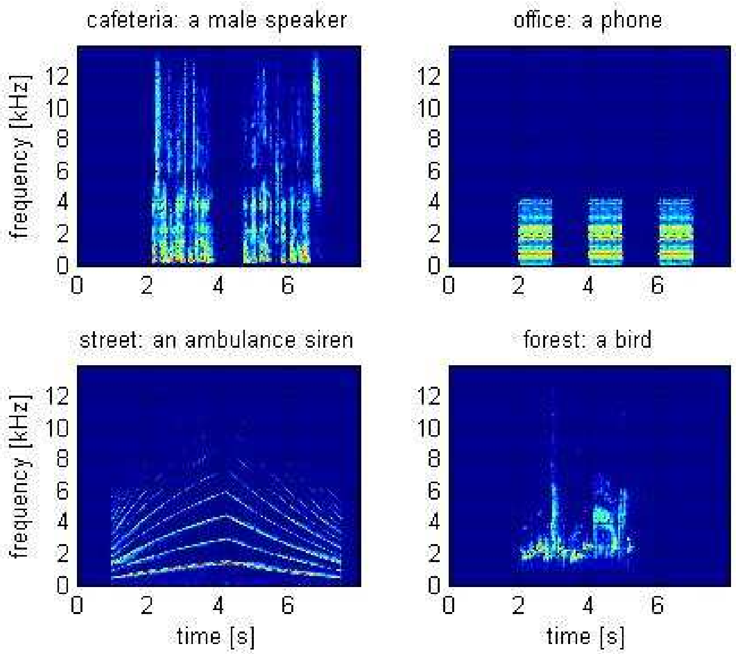

***Figure 2**: Target signals of the four scenes*

We implemented four realistic noisy scenarios: a crowded cafeteria, a busy office, a noisy street and a windy and noisy forest. In each of the scenes the test subjects were asked to localize a target sound source (a male speaker, a telephone, an ambulance, a bird) in the scene-dependent noise (babble noise, office machine and babble noise, street noise, wind and river noise). The target signals are shown in Fig 2. The interfering signals were real recordings of ambient noises. They were played incoherently over 12 positions in the horizontal plane (30° spacing), producing a highly diffuse sound field. The target signals were played at 60 dB. The SNR was set to 5 dB, as determined via the measured rms values of the signals.

In the first experiment, the quality of the simulation was verified by comparing localization performance between full loudspeaker playback and virtual simulation. In a second experiment, we compared a static beamformer, a noise canceller and the omnidirectional condition, in which no processing was applied to the behind-the-ear (BTE) microphone signals. Twelve normal hearing subjects took part in the experiment. The test subjects completed the tasks in six sessions of two hours each.

In both experiments, the target sound was presented four times from random positions around the listener after an initial training phase. No feedback was provided during the test and no loudness roving was applied between positions. The training phase consisted of an initial orientation sequence in which each position was played once starting from the front and moving around the listener counter clockwise. This was followed by a training run, in which every position was played once in random order and feedback was given to the test subject.

Results and Discussion

The accuracy of localization was measured using the angular root-mean square (rms) error and the amount of front/back confusions. Front/back confusions occur when a sound presented in the front is heard in the back and vice-versa. These two phenomena are different types of errors and therefore were analyzed separately. The standard angular rms error is particularly sensitive to front/back confusions. To remove this effect, we resolved the front-back confusions prior to measuring the directional error (Langendijk et. al, 2001). We define the rms error as:

$$rms = \text{mean}_\theta \left[\sqrt{\sum_{i=1}^{N} \left(\text{asin}\left(\sin x_\theta\right) - \text{asin}\left(\sin y_{\theta,i}\right)\right)^2} \right] \qquad \textbf{(1.1)}$$

where x_θ is the position played at angle θ and $y_{\theta,i}$ the response given by the test subject at test iteration i. N is the total number of repetitions.

Experiment 1: virtual sound localization

The results show that the localization ability constantly varied over the scenes, depending on the set of cues available in the target sound. The average results are shown in Table I. A similar directional error wss obtained between external and internal presentation. No statistically significant difference could be found between both presentation methods, due to the large standard deviations and the limited number of test subjects (see Fig. 3).

	cafeteria		office		Street		forest	
	loudsp.	simulation	loudsp.	simulation	loudsp.	simulation	loudsp.	Simulatio n
rms [°]	2.2	3.9	4.7	7.2	7.1	8.0	10.5	11.7
f-b [%]	1.0	7.5	11.7	10.8	6.5	13.1	10.4	10.4

Table I: *Mean results of the first localization test, for the four scenes.*

Front-back confusions were however larger for the simulations for the cafeteria and the street scenes only. Statistical significance was found for the cafeteria condition only.

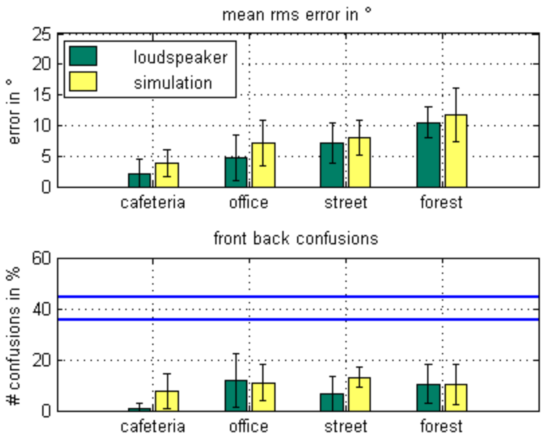

Figure 3: *Angular rms errors in [°] for every presentation angle for the three conditions and the four scenes.*

Experiment 2: localization with behind-the-ear hearing aids

Results of the second experiment showed that the hearing aid algorithms alter spatial auditory perception differently. Table II summarizes the results.

	cafeteria			office			Street			forest		
	omni	beam	NC	omni	beam	NC	omni	Beam	NC	omni	beam	NC
rms [°]	7.9	10.3	8.7	8.2	7.0	8.3	11.2	12.7	11.8	15.4	16.2	16.1
f-b [%]	39.0	1.9	39.2	40.8	1.0	37.1	45.4	3.8	48.3	47.3	1.5	43.3

Table II: *Mean results for the BTE localization test. "omni" stands for omnidirectional, "beam" for beamformer and "NC" for noise canceller.*

Compared to the reference condition, localization with the hearing aid algorithms was significantly worse, for all the scenes tested. The results are shown in Fig. 4, on the left. For the omnidirectional and the noise canceller conditions, the number of front-back confusions appeared to be at chance level (between the blue lines). The attenuation effect of the beamformer (sounds presented at the back are softer) apparently helped the subjects to differentiate sounds played at the back from those played at the front. By analyzing the rms errors separately in the front and in the back (Fig. 4, right), the attenuation effect of the beamformer is clearly visible. For all the scenes except the cafeteria, performance in the front was close to the reference condition. In the back, however, the rms error increased significantly, due to a lower signal-to-noise ratio.

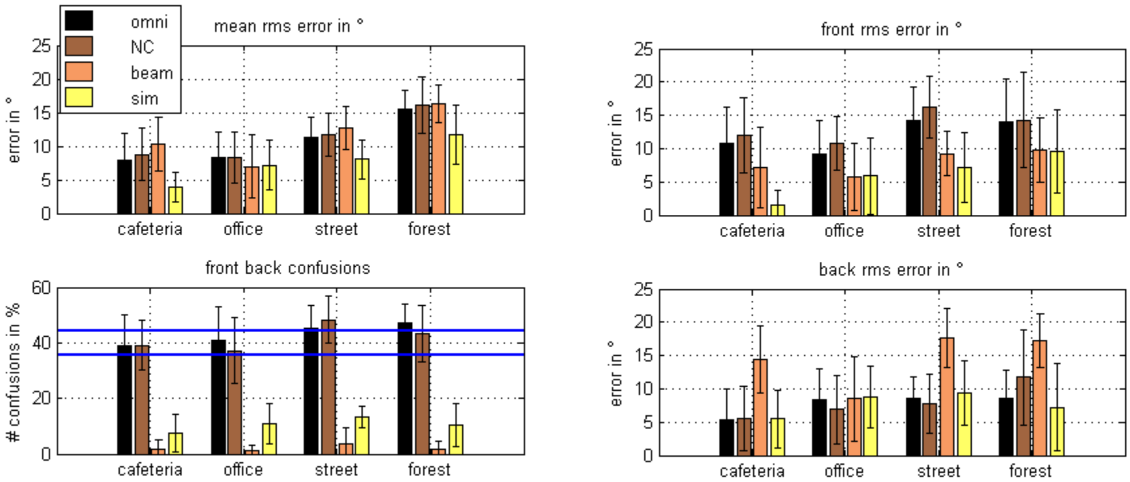

***Figure 4**: Localization performance for the omnidirectional, noise canceller, beamformer and the reference simulation (sim) conditions (left). On the right, front and back rms errors are shown separately.*

Conclusions

Our results show that virtual acoustics can be used reliably to evaluate the spatial quality of bilateral hearing aids. For all implemented scenes, localization performance with our virtual system was close to reality. However, due to the lack of head movements in the simulations, sound coming from the front was often perceived 'in the head' and increased the number of front-back confusions for the cafeteria scene.

Performance with the hearing aid CIC shells was significantly worse than performance in the reference condition. Due to the microphone position, pinna effects were absent leading to a more diffuse sound percept and an increase in the number of front-back confusions. The directivity characteristics of the beamformer recreate an artificial pinna that allows the hearing aid user to distinguish between front and back. For this algorithm, performance in the front was close to the reference condition.

References

Langendijk, E. H. A., Kistler, D. J., and Wightman, F. L. (2001). "Sound localization in the presence of one or two distracters", Journal of the Acoustical Society of America 109, 2123–2134.

Schimmel, S., Mueller, M., and Dillier, N. (2009). "A fast and accurate shoebox room acoustics simulator", in *Proc. of IEEE Int. Conf. on Acoustics, Speech and Signal Processing (ICASSP)*, 241–244, roomsim.sourceforge.net

Van den Bogaert, T., Klasen, T., Moonen, M., Deun, L. V., and Wouters, J., (2006). "Horizontal localization with bilateral hearing aids: Without is better than with", Journal of the Acoustical Society of America 116, 515–526